Aviation Safety Benefits of NASA Synthetic Vision: Low Visibility Loss-of-Control, Runway Incursion Detection, and CFIT Experiments

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A national aviation safety goal was established to reduce the accident rate by 80% by 2007. Reducing low visibility as a causal factor in general aviation and commercial accidents may help meet that goal. The paper describes research conducted at the NASA Langley Research Center on the efficacy of synthetic vision to mitigate spatial disorientation, runway incursions, and controlled-flight-into-terrain.

Keywords: Synthetic Vision; Spatial Disorientation; CFIT; Runway Incursion; Inadvertent IMC

Introduction

Flying is safe. The worldwide commercial aviation major accident rate is low and has remained nearly constant over the past two decades. However, the demand for air travel is expected to increase over the coming two decades, more than doubling by 2017. Without an improvement in the accident rate, such an increase in traffic volume would lead to a projected 50 or more major accidents a year worldwide - a nearly weekly occurrence. Given the very tragic, and damaging effects of a single major accident, this situation would deliver an unacceptable blow to the aviation system. As a consequence, the anticipated growth of the commercial air-travel market may not reach its full potential.

Aviation Safety Program

To ensure the public trust, a national goal was established to reduce the aviation fatal accident rate by 80% by 2007. NASA stepped up to this challenge by forming the Aviation Safety Program (AvSP), which is part of the NASA Aerospace Technology Enterprise (NASA, 2001). The AvSP program has a number of research projects developing technologies to help meet the national safety goal. Among aviation safety enhancement strategies, NASA is working toward the reduction of low-visibility as a causal factor of aircraft accidents.

Synthetic Vision Systems Project

Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. In commercial aviation alone, over 30-percent of all fatal accidents worldwide are categorized as Controlled Flight Into Terrain (CFIT), where a mechanically sound and normal functioning airplane is inadvertently flown into the ground, water, or an obstacle, principally due to the lack of outside visual reference and situational awareness (Wiener, 1977). Other types of accidents involving restricted visibility combined with compromised situational awareness include spatial disorientation and runway incursions.

The AvSP Synthetic Vision Systems (SVS) project is developing technologies with practical applications that will eliminate low visibility conditions as a causal factor to civil aircraft accidents, as well as replicate the operational benefits of flight operations in unlimited ceiling and visibility conditions, regardless of the outside weather or lighting condition. The technologies will emphasize the cost-effective use of synthetic/enhanced-vision displays; worldwide navigation, terrain, obstruction, and airport databases; and Global Positioning System (GPS)-derived navigation to eliminate “visibility-induced” (lack of visibility) errors for all aircraft categories. A major thrust of the SVS project is to develop and demonstrate affordable, certifiable display configurations that provide intuitive out-the-window terrain & obstacle information, including advanced pathway and guidance information for precision navigation, obstacle/obstruction avoidance, and runway incursion detection. SVS display concepts employ computer-generated terrain imagery, on-board databases, and precise position and navigational accuracy to create a three dimensional perspective presentation of the outside world, with necessary and sufficient information and realism, to enable operations equivalent to those of a bright, clear, sunny day regardless of the outside weather condition. The safety outcome of SVS is a display that should help reduce or even prevent CFIT, which is the single greatest contributing factor to fatal worldwide airline and general aviation accidents (Boeing, 1998). Other safety benefits include reduced runway incursions and loss-of-control accidents (Prinzel et al., 2000; 2001; 2002; 2003; Prinzel et al., in press; Williams et al., 2001).

Prevention of Spatial Disorientation

General aviation (GA) accounts for 85 percent of the total number of civil aircraft in the United States. Of the 1,820 accidents in 2002, 1,714 were general aviation with 342 fatal accidents. Although the number of accidents has decreased slightly, the accident rate remains unacceptable at 6.56 accidents per 100,000 flight hours. The majority of fatal GA accidents (67.8%) were the result of pilot-related causes. The overwhelming majority of these accidents took place during instrument meteorological conditions (IMC), which produced almost three times the rate of fatal accidents than flights under visual meteorological conditions (VMC; AOPA, 2001). To help reduce the GA accident rate, NASA is developing GA synthetic vision technologies that could help to mitigate or even prevent spatial disorientation accidents through an intuitive display for VMC-type flight in IMC.

Several experiments have been conducted to evaluate the efficacy of synthetic vision for enhancing aviation safety for GA aircraft. One of these studies focused on whether SVS could help reduce or prevent low visibility, loss-of-control accidents for low-hour visual flight rules (VFR) pilots. The objective of the experiment was to establish the benefits of a synthetic vision for inadvertent IMC (iIMC) situations wherein the VFR pilot accidentally enters clouds and loses the visual horizon. A significant number of accidents happen each year because pilots lose spatial awareness and experience loss-of-control during these iIMC events. VFR flight into IMC is a major hazard in general aviation (O'Hare & Owen, 2000), and 75-80% of accidents classified as inadvertent IMC were fatal compared to 18% of all other GA accident categories (Goh & Weigmann, 2001). Clearly, prevention of spatial disorientation accidents would significantly improve the safety of Part 91 operations. Because many of these accidents are due to a loss of visual cues, researchers at the NASA Langley Research Center (LaRC) evaluated whether synthetic vision displays could mitigate these types of accidents.

Low Visibility, Loss-Of-Control Experiment

The experiment evaluated three displays while 18 low-hour (< 400 hours) pilots executed four maneuvers during iIMC scenarios. The three displays were (a) baseline Cessna-172 instruments, (b) Electronic Attitude Indicator (EAI), and (c) SVS display (Figure 2). The baseline display represented what is currently available on GA aircraft. The EAI display was designed to be more representative of "glass cockpits" and included advanced flight symbology, such as a velocity vector. The third concept was the SVS display that was similar to the EAI display except the blue-sky/brown-ground background was replaced by synthetic terrain. The four scenarios were: straight-and-level flight while maintaining airspeed, altitude, and heading in IMC; 180º turn with a 20º bank upon entering IMC while maintaining altitude and airspeed; descend 1,000 ft. upon entering IMC while maintaining heading and airspeed; and climb 1,000 ft. upon entering IMC while maintaining heading and airspeed.

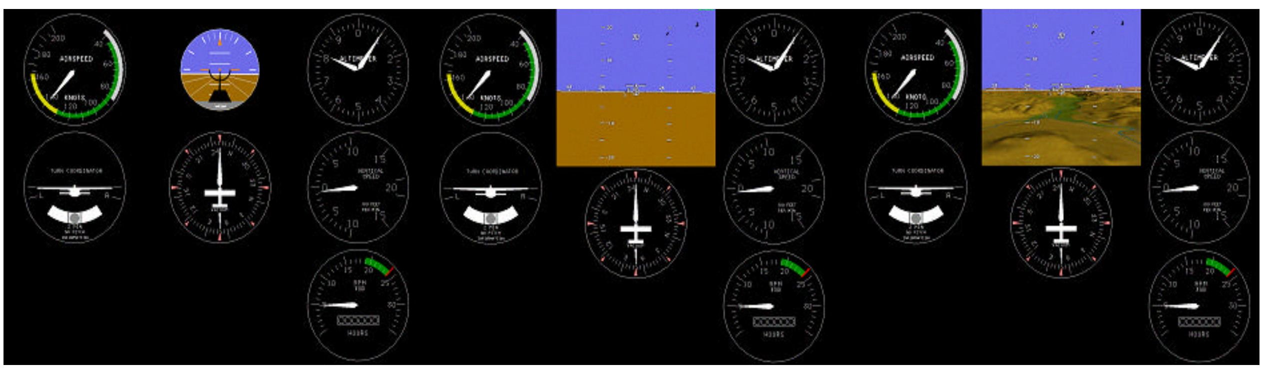

Figure 1. Three NASA Synthetic Vision Displays Used in Low Visibility, Loss-Of-Control Experiment

Several pilots failed to maintain pilot technical standards (PTS) with either the baseline or EAI displays. One pilot experienced a significant loss of situation awareness using the baseline display and became totally disoriented during the 180º maneuver. In comparison, pilot performance was found to be significantly better with the SVS display during each of the four maneuvers (Glabb & Takallu, 2002; Takallu, Wong, & Uenking, 2002). Future research will validate these results in a motion-based GA simulator to simulate the physiological mismatches experienced during spatial disorientation.

Controlled Flight Into Terrain

Aviation has been witness to rapid advancement in technologies that have significantly improved aviation safety. The development of attitude indicators, flight management systems, radio navigation aids, and instrument landing systems (ILS) have extended aircraft operations into weather conditions with reduced forward visibility. However, as Brooks (1997) has noted, "…while standard instrumentation has served us well, enabling aviation as we see it today, literally thousands of dead souls, victims of aviation catastrophe, offer mute and poignant testimony to its imperfections. The simple, elegant dream of soaring aloft *visually*, *intuitively* – bird-like – remain elusive" (Italics added, p. 17).

Pilots must cope within an alphanumeric "filter of symbology" to achieve spatial awareness, which has repeatedly met with deadly consequences. The significant number of CFIT accidents testifies to the danger of losing situation awareness with these "coded" displays (Theunnissen, 1997). Approximately 40% of all aircraft accidents are CFIT and account for 50% of all aircraft fatalities (Mathews, 1997). Because CFITs account for a significant proportion of aircraft fatalities, prevention of these accidents would significantly reduce the accident rate for both commercial and GA aircraft. Often, these accidents are caused because of limited visibility which synthetic vision may help to mitigate.

SVS displays provide a natural presentation of the outside world with information that is intuitive and easy to process. Essentially, it provides a "picture" of the outside world, rather than disparate pieces of alphanumeric information, and best supports humans' natural acquisition and encoding of the world. As the old Chinese proverb goes, "One picture is worth a thousand words". But, in aviation terms, it may be more appropriate to say, "One picture is worth a thousand alphanumerics" (Brooks, 1997) and "…a thousand lives" (Prinzel et al., 2003).

NASA research has successfully evaluated the safety and operational benefits of synthetic vision, but only during nominal, restricted visibility operations (e.g., Glaab & Takallu, 2002; Prinzel et al., 2002; Prinzel et al., in press). Although the research has consistently shown the advantage of synthetic vision compared to traditional instruments for complex approaches to terrain- (EGE, ROA, AVL) or operational-challenged airports (DFW), the true safety value of SVS would be to reduce or eliminate off-nominal situations that present significant safety risks, such as prevention of CFIT. Therefore, two experiments were conducted to evaluate the efficacy of synthetic vision for CFIT prevention.

General Aviation CFIT Experiment

The first experiment focused on general aviation and introduced an inadvertent IMC scenario with an altimeter error. The inadvertent IMC anomaly scenario was designed to show that an otherwise unavoidable CFIT situation could be prevented with synthetic vision technology. Therefore, a baseline display was not evaluated because even highly experienced pilots were unable to avoid a CFIT during preliminary testing. The displays that were tested were based on three different SVS texturing methods: Constant Color (CC), Elevation-Based Generic (EBG), and Photo-Realistic (PR). CC replicates an industry concept that the FAA has certified under the SafeFlight 21 Capstone-II program. The EBG concept uses shades of green with darker shades representing higher terrain. Finally, the PR concept was derived from 4-meter satellite imagery data. The display concepts were combined with 1, 3, or 30 arc-sec digital elevation models (DEM). A 500 x 500 ft grid fishnet was also evaluated.

Pilots flew 34 experimental runs prior to the CFIT scenario (35 total). The CFIT scenario resembled 11 of the previous 34 trials that began straight-and-level at 6500 ft MSL (4000 ft AGL) with instructions to make a left-bank turn and descend after two minutes to 5000 ft MSL (1000 ft AGL) over rising terrain. The scenario began in VMC with visibility deteriorating to IMC within one-minute elapsed time. The CFIT scenario started at 5000 ft MSL, but the altimeter showed 6500 ft MSL. Therefore, the instruction to reduce altitude by 1500 ft in effect descended the aircraft to -500 ft below the mountain peaks directly in front of the aircraft.

Only 15% (2/14) of the VFR pilots and none (0/13) of the professional pilots experienced a CFIT while using the SVS displays. One of these 14 VFR pilots had significant difficulty flying the aircraft throughout the entire experimental session and analysis showed performance to be well outside practical pilot standards; therefore, the data for this pilot should be considered an outlier. The other pilot, however, did experience a CFIT event and, during the semi-structured interview, reported awareness that something was wrong but felt captured by the incorrect MX-20 reading and failed to crosscheck. Despite this CFIT, the results provide strong evidence that synthetic vision can significantly enhance terrain awareness under low-visibility conditions that otherwise would result in an unavoidable CFIT accident.

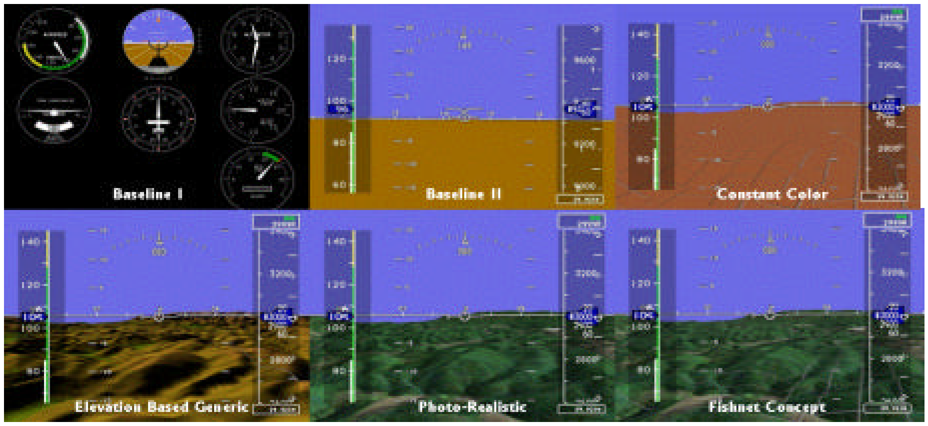

Figure 2. NASA GA Synthetic Vision Displays Used in CFIT Experiment

Commercial Aviation CFIT Experiment

The second CFIT experiment focused on commercial air transport pilots and introduced a lateral path error in flight management system guidance that brought the aircraft into close proximity with terrain during a go-around procedure. Pilots were asked to fly a circling approach to Eagle-Vail, CO (EGE) runway 07 under CAT IIIa and execute a go-around 200 ft AGL and intercept the 059 radial from SNOW VOR (SXW). The aircraft model was a Boeing 757, and both the approach and departure speed target was 140 knots. All scenarios were flown with moderate turbulence. At 200 ft AGL, a go around was executed and the climb gradient performance was degraded. The pilot raised the landing gear and the flaps were set to go-around configuration. The evaluation pilot was instructed to use speed-on-pitch to maintain 140 knots and follow the departure path that provided escape guidance through a “notch” between two mountain peaks. The run ended at the 12.0 DME point from SXW. For the CFIT scenario (run 22 of 22), the flight guidance was altered on the departure path. A Terrain Awareness Warning System (TAWS) and Vertical Situation Display (VSD), however, were available on the navigation display for both baseline and SVS. The display concepts were: (a) baseline EFIS 757 display, (b) size A (5.25” x 5.25”) display with SVS, (c) size X display size (8”x10”) with SVS, and (d) HUD enhanced with SVS. The order of display presentation was randomized across evaluation pilots. Twelve of the 16 evaluation pilots flew the CFIT scenario with a SVS enhanced PFD or HUD and 4 pilots flew with the Baseline display.

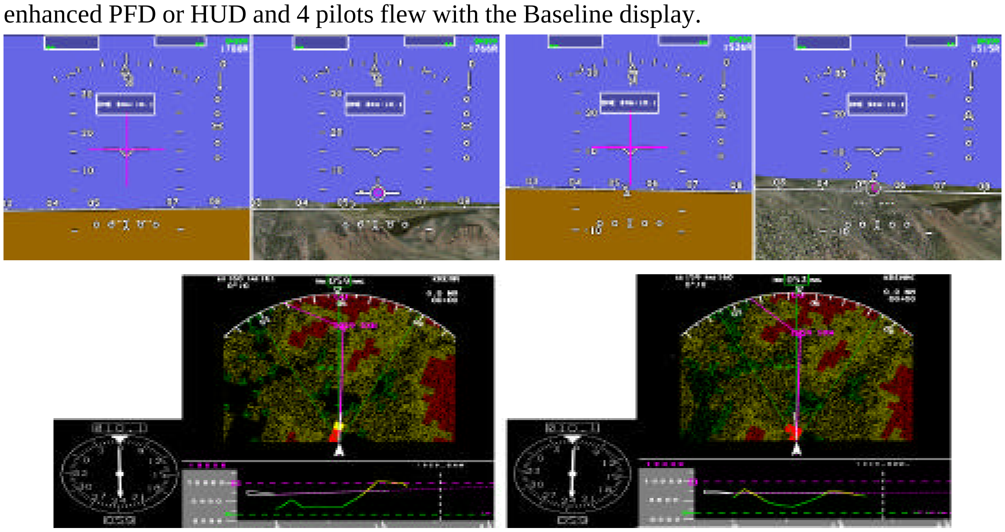

Figure 3. Commercial CFIT Displays During Nominal (Left) and CFIT (Right) Scenarios

One significant result was that all four Baseline pilots (100%) had a CFIT event, but none (0%) of the twelve SVS pilots did. On average, pilots with a SVS display noticed the potential CFIT 53.6 seconds before impact with the terrain. Three of the 4 pilots impacted the terrain while one passed within 58 feet of a mountain peak (topped trees on mountain). Even though the baseline concept had a Radio Magnetic Indicator (RMI), TAWS and VSD enhanced ND, none of the Baseline pilots were aware until after the CFIT event had occurred. Pilots rated the baseline concept to be “moderately high” on the modified Cooper-Harper workload scale and to be “very low” for situation awareness (SART) during the departure task. SA-SWORD paired comparison rankings confirmed that SVS displays significantly enhanced situation awareness for CFIT detection.

Runway Incursion Detection

Runway incursions are a serious aviation concern. The number of reported incursions rose from 186 in 1993 to 383 in 2001, an increase of 106 percent. In 1990, the National Transportation Safety Board (NTSB) has listed runway incursions as a “top 10” of most wanted transportation safety improvements. The FAA has begun several initiatives to reduce the number of runway incursions, including an alerting system for ATC, which is relayed via voice communication to the cockpit. However, no system is currently available onboard aircraft to provide the flight crew runway incursion alerts. NASA developed a Runway Incursion Prevention System (RIPS) to help provide this information to flight crews.

Attention Capture Experiment

Head-up displays (HUDs) provide primary flight, navigation, and guidance information to the pilot in a forward field-of-view on a head-up transparent screen. Because HUDs reduce time head down, they enhance pilot performance and situation awareness through simultaneous scanning of both instrument data and the out-the-window scene (e.g., Wickens & Long, 1995). However, research has also documented the phenomenon of “attention capture” and problems detecting unexpected events, such as another aircraft on the active runway during landing. Because synthetic vision HUDs may present compelling near-domain information, there are concerns about whether the pilot can transition to the far domain when the synthetic terrain is removed.

Research was conducted using a rare-event scenario in which a B-737 taxied beyond the hold line and presented a runway incursion situation. The experiment was part of research to evaluate pathways displays presented on a SVS HUD while pilots flew complex, curved approaches in simulated CAT IIIa conditions. Nine 757 Captains with HUD experience participated in the experiment. Fourteen approaches using the Reno Sparks 16R Visual Arrival were made in a B-757 fixed-based simulator. In addition, a runway incursion scenario was flown in which the pilot was forced to make a go-around to avoid a 737 on the active runway. Pilots were not given the option to “de-clutter” the synthetic terrain and instead it was automatically removed just before decision height making the scenario a “worse case” for runway incursion detection.

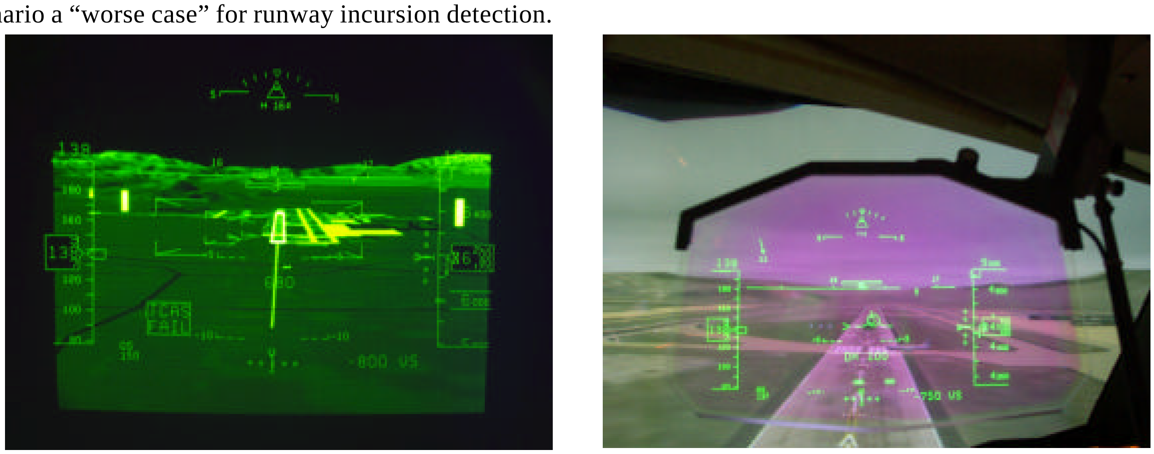

Figure 4. Head-Up Displays On Approach (Left) and At Decision Height (Right) During Rare-Event Scenario

Only one (1/9) of the commercial pilots failed to notice the transport aircraft on the active runway. During the post-experimental interview, he acknowledged that he saw the aircraft but it was too late to initiate the go-around and decided to land. The pilot felt that the situation did not pose any danger since he could land the aircraft further down the runway well beyond the incursion aircraft. Therefore, these results support that a synthetic vision HUD does not significantly decrease unexpected event detection. However, to further safeguard against incursions, the AvSP has incorporated RIPS technology to be used as part of the NASA synthetic vision system.

Runway Incursion Prevention System

RIPS integrates airborne and ground-based technologies to provide: (1) enhanced surface situation awareness to avoid blunders and (2) runway conflict alerts in order to prevent runway incidents and improve operational capability. The system monitors for potential incursions using incursion detection algorithms that provide both aural and graphical alerts. The alerts can be presented on a HUD, PFD, or electronic moving map (EMM). RIPS also enhances situation awareness by providing graphical guidance during rollout, turn-off, and taxi. The EMM displays a graphical perspective airport layout, current ownship position, traffic, and ATC instructions. Together, RIPS has been demonstrated to significantly increase situation awareness and eliminate the occurrence of runway incursions during both simulation (e.g., Jones, 2002) and flight tests (e.g., Jones, Quach, & Young, 2001).

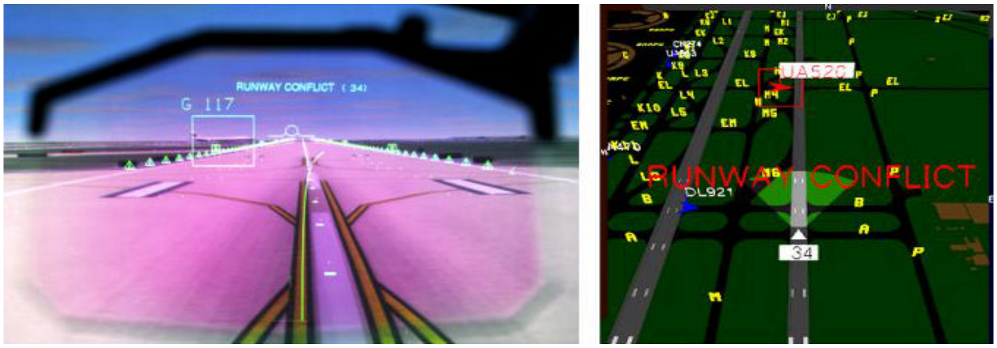

Figure 5. Runway Conflict Alert Presented On HUD (Left) and EMM (Right)

Conclusions

The paper describes the aviation safety benefits of the NASA Synthetic Vision System, and presents a sample of research that has been conducted to demonstrate the efficacy of SVS to meeting national aviation safety goals. Synthetic vision is composed of several technologies that include SVS navigation displays; RIPS; integrity monitoring; enhanced vision sensors; taxi and surface maps; and advanced communication, navigation, and surveillance. Together, these technologies represent a comprehensive solution to problems of restricted visibility. Future research is planned for GulfStream-V and 757 flight tests that will evaluate these technologies as part of an integrated system. Research is also ongoing for simulation research, including synthetic navigation displays, 4D tunnels, helmet-mounted displays, and synthetic/enhanced sensor blending.

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